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White Paper:

OPTIMAL MOUNTING CONFIGURATION FOR BIFACIAL SOLAR MODULES ON SINGLE AXIS TRACKERS

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This report was compiled in part based on analysis of data collected by GameChange Solar LP ("GameChange") from third party solar PV project owners and installers and from observations of GameChange personnel. The report is presented as-is without any warranties or guarantees as to the accuracy of the information presented herein. GameChange will not be responsible for any parties relying on the information or conclusions in this report.

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1.0 Executive Summary

With the increasing popularity of bifacial solar modules, solar racking manufacturers have introduced single axis trackers with various mounting configurations into the market. This study aims to identify the most financially preferable mounting configuration from the standpoint of project ownership, accounting for relative racking structure costs, relative installation costs, and energy production.

The following mounting configurations were analyzed as part of this study. Please note, the H values refer to normalized height which compares collector width to the height of the tracker table (and therefore module clearance).

- 1-Up Portrait, H = .9 (roughly 40" ground clearance)
- 2 Up Landscape, H = .9 (roughly 40" ground clearance)
- 2-Up Portrait, H = .7 (roughly 40" ground clearance)
- 2-Up Portrait, H = .9 (roughly 80" ground clearance)

Energy Production modeling was performed using the System Advisor Model (SAM) software developed by NREL which determines rear side irradiance gain accounting for normalized height of the rack, how structure shades the rear side of the module and portrait vs. landscape module orientation. Structural analysis was performed on each mounting configuration by a licensed Professional Engineer. The relative cost of the rack for each configuration was identified. Relative costs for installation were also determined. Finally, financial models for the applicable configurations were created accounting for total project CAPEX, O&M, and revenues from energy production including module degradation.

The financial analysis of these configurations showed that the 1-Up Portrait configuration provides the best financial performance for project ownership, assuming consistent module degradation. 2-Up Landscape configuration exhibited the 2nd best financial performance provided that the project is in a location where the climatic loads do not exceed the short-side mounting mechanical ratings of the module. The 2-Up Portrait configuration provides the least preferable financial performance for the project ownership.

However, it is understood that structure obstructing a portion of the backside of bifacial modules creates hot spots due to the mismatch of irradiation on the rear side of the cells between the portion of the cell in the shadow of the structure and the portion of the cell receiving the rear side irradiance. This mismatch is likely to result in accelerated degradation of the solar modules, which will have an adverse impact on project financials for configurations where structure exists behind the bifacial modules, such as the 1-Up Portrait configuration. As of the writing of this paper, multiple organizations are studying this phenomenon to identify the rate of accelerated degradation due to backside irradiance mismatch. Until it is confirmed that the 1-Up portrait mounting configuration does not have a significant impact on bifacial module degradation rate, the recommended mounting configuration for bifacial solar modules on a single axis tracker for projects with relatively light climatic loads is 2-Up Landscape.

2.0 Background

2.1 Bifacial Modules

A growing trend in the Solar PV industry in the United States is the use of bifacial solar modules. Per PV Magazine "The bottom line is that bifacial panel use on trackers is expected to grow to a double digit share within a year, and eventually become the dominant design."[1] This view is reinforced by the level of interest shown by solar developers and EPCs at trades shows such as SPI and an increasing number of requests made to racking suppliers, such as GameChange Solar (GameChange), for both fixed tilt and single axis tracker systems to support bifacial modules.

Bifacial modules produce solar power from both sides of the module. Whereas traditional opaque-backsheet panels (monofacial modules) are only designed to convert solar irradiance from one side of the module into DC power, bifacial modules are manufactured with clear plates on both the front and backside of the solar cells and are designed to convert solar irradiance from both sides into DC power. Similar to monofacial modules, bifacial modules come in a variety of types including framed and frameless.

A critical parameter for the increase in energy output due to bifacial modules is the amount of light that is being reflected off of the ground and other surfaces. The proportion of light that is being reflected is referred to as albedo. Albedo varies widely by material, from up to 90% for white snow to 25% for green grass down to 10% for asphalt.

It is also important that nothing obstructs the light reflecting off the ground from hitting the back side of the solar modules. Any obstructions will cast a shadow on the rear side of the module, reducing the amount of energy the module is producing. Obstructions on the back side of the module could also cause a mismatch of the amount of light (irradiance) that is hitting different parts of solar cells in the bifacial module, causing a hot spot to form and potentially accelerating the degradation of the module. Depending on how the steel racking structure supporting the modules is designed, it could act as such an obstruction, blocking some of the reflected light from hitting the back side of the module. As such, it is important to study the impact of the racking structure on bifacial modules, which is the purpose of this report.

2.2 Common Racking Configurations

As stated above, the configuration of the racking structure is important in that any structure behind bifacial solar modules will prevent solar irradiance from hitting the back side of the module and therefore reduce the increase in power production from the back side of the module. The term "configuration" is used to describe the way the panels are oriented, the number of panels "up" and the mounting method.

Solar module orientation is typically referenced relative to the predominant normal direction of the solar irradiance. For fixed tilt systems in the United States, the solar irradiance is predominantly from the South. For single axis tracking systems, the panels track such that the panels are normal to the sun in the East-West direction.

Solar modules can be oriented in either Portrait, with the long side parallel to the direction of predominant solar irradiance (North-South in a fixed tilt system, East-West for a single axis tracker) or Landscape, with the short side parallel to the direction of predominant solar irradiance (East-West in a fixed tilt system, North-South for a single axis tracker). Portrait and Landscape configurations for a single axis tracker are shown in the images below:

Figure 2-1a: Panels in a Portrait Orientation

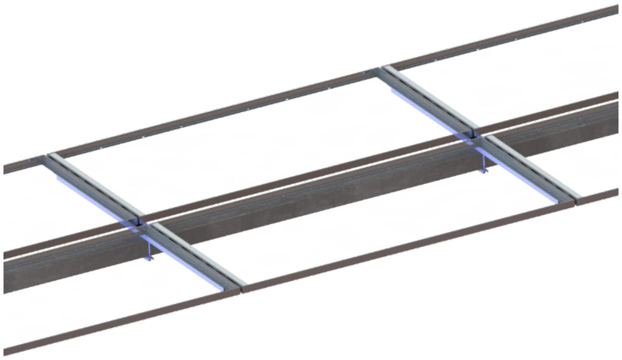


Figure 2-1b: Panels in a Landscape Orientation

The number of modules "Up" is the number of rows of modules supported by a single racking structure. The traditional configuration for a single axis tracker is to have one row of modules oriented with the long side of the module parallel to the East-West direction, i.e. a 1-Up Portrait Configuration.

There are many ways to mount (i.e. connect) solar modules to a racking structure, however for the purposes of this study all panels are assumed to use a traditional "bottom mount" where the solar module frames are bolted directly to the racking structure.

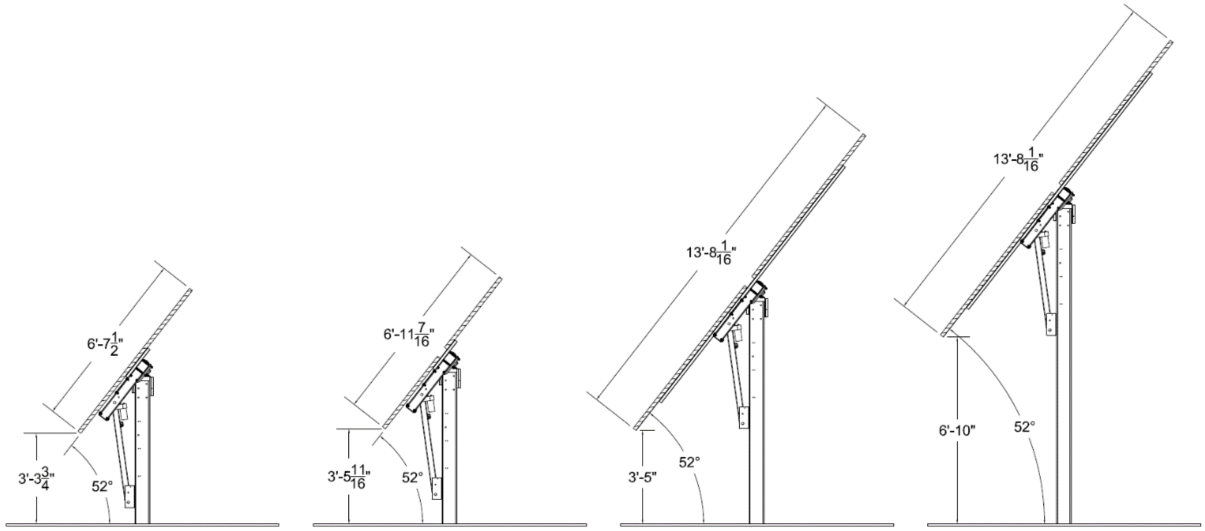
2.3 Configurations Considered in this Study

This study focuses only on single axis trackers with the axis of rotation oriented North-South (the modules rotate to face the East or West). Four tracker configurations are considered:

- Configuration A: 1-Up Portrait, H = 0.9
- Configuration B: 2 Up Landscape, H = 0.9
- Configuration C: 2-Up Portrait, H = 0.7
- Configuration D: 2-Up Portrait, H = 0.9

The normalized height parameter (H) is a way to determine the relative depth of the shadow behind the modules and is described in more detail below.

See the figure below for graphic representations of the four configurations. Note, for all 2-Up configurations a gap exists between the rows of modules so no portion of a module is directly over the torque tube.



1-Up Portrait
Normalized Height ~ 0.9

2-Up Landscape
Normalized Height ~ 0.9

2-Up Portrait
Normalized Height ~ 0.7

2-Up Portrait
Normalized Height ~ 0.9

Figure 2-2: Tracker Configurations

The traditional configuration for a single axis tracker is to have one row of modules oriented with the long side of the module parallel to the East-West direction, i.e. a 1-Up Portrait Configuration. However, this configuration causes the torque tube (a.k.a. row tube) rotating the panels on the tracker table to be located directly below the middle of the modules. Thus, this configuration is suboptimal from the standpoint of backside irradiance gain.

However, by utilizing a 2-Up configuration, the modules can be located such that neither row of modules is directly above the torque tube. Furthermore, by locating the purlins, the East-West members that the modules are mounted to, with the North-South gaps between the modules, the tracker can be designed with no structure behind the backside of the modules. This is ideal from the standpoint of backside irradiance gain.

See the images below for 3-D views of the configurations considered in this study:

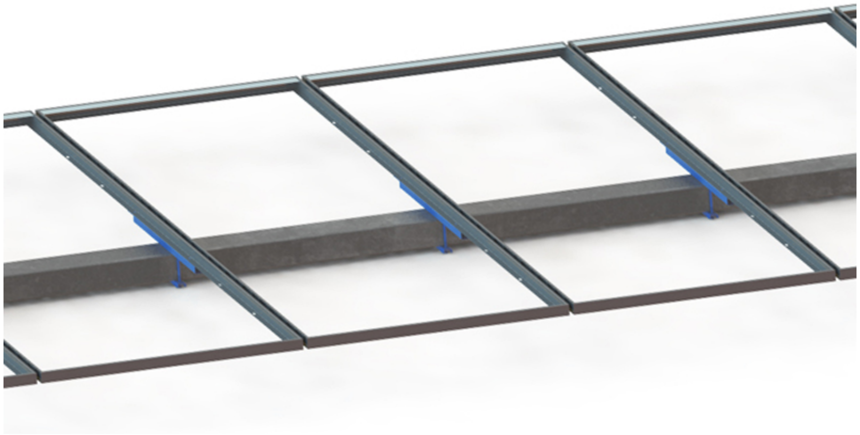


Figure 2-3a: 1-Up Portrait Structure

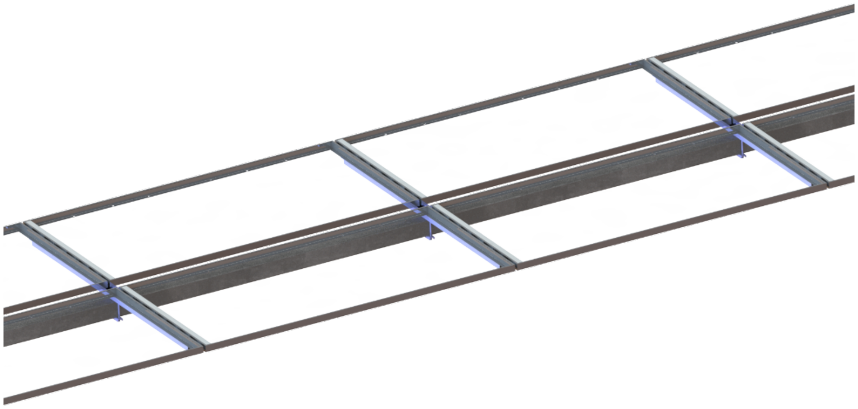


Figure 2-3b: 2-Up Landscape Structure

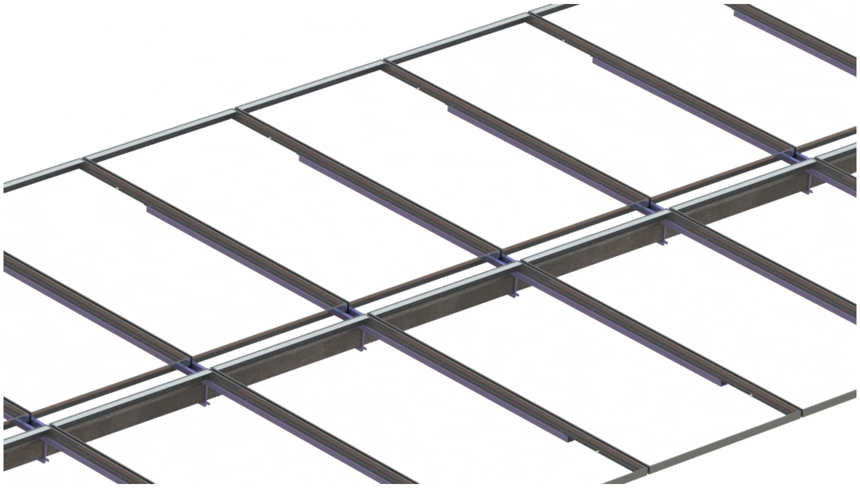


Figure 2-3c: 2-Up Portrait Structure

As is described in more detail in the Energy Modeling section below, the ratio of the collector width (a.k.a. chord length) to the panel clearance impacts the depth of the shadow behind the modules and therefore the power gain from the backside of the modules. Due to the minimum panel clearance being a function of the Range of Motion for a given tracker project, this phenomenon can more readily be compared using a normalized height (H) parameter:

$$H = \frac{Axis\ Height}{Collector\ Width}$$

For the 2-Up Portrait configuration, two normalized axis heights are considered: 0.7 and 0.9. For a typical bifacial module, with a panel length of ~2m, the H = 0.7 configuration corresponds to roughly a 1m [40"] ground clearance whereas the H = 0.9 configuration corresponds to a roughly 2m [80"] ground clearance. The 1-Up Portrait and 2-Up Landscape configurations utilize a normalized axis height (H) of 0.9 and ground clearance of roughly 1m [40"]. See the NREL paper "Model and Validation of Single-Axis Tracking with Bifacial PV"[2] for more information on the impact of normalized axis height on bifacial energy gain.

While Configuration D (2-Up Portrait, H = 0.9) has advantages from a backside irradiance gain standpoint, the increased post stickup height causes the cost of the racking structure, in particular the posts of the tracker, to increase significantly. Furthermore, the increased height of the torque tube above grade greatly increases the complexity and therefore cost of installation regarding fall protection. As such, although energy modeling was performed for this configuration, financial analysis was not performed as it is not the optimal configuration by inspection.

3.0 Annual Energy Production Analysis

3.1 Energy Modeling

The annual energy production (AEP) values used in this report were determined using the System Advisor Model (SAM) software program developed by the U.S. National Renewable Energy Laboratory (NREL). SAM was selected over other energy modeling softwares, including PVSyst, due to the robustness of the bifacial energy analysis.

The correlation between bifacial energy gain estimated using SAM and real-world results is well documented in NREL publications. The view-factor model that SAM uses is more granular as well as more conservative in the computation of additional irradiance received on the back of the module than PVSyst, and thus has less of a chance of overestimating production. PVSyst, breaks up the range of rotation into 7 segments and precomputes backside irradiance for each segment. Interpolation is then used for time steps in between the precomputed angles which is less granular and therefore not as preferable as SAM. Furthermore, the algorithm for SAM takes into account the normalized height of the rack and allows for the input of losses due to racking structure behind the module affecting the rear side irradiance. Finally, SAM also allows trackers to be modeled with different module orientations, allowing for the comparison between landscape and portrait configurations, which was critical to the analysis shown herein. As a result, SAM, more specifically, version SAM 2018.11.11, was used to perform the energy modeling analysis shown herein.

Five energy models were performed. In addition to the four bifacial module configurations described above, a "control" model was created to determine the annual energy production of a monofacial module with a 1-Up Portrait configuration.

This study assumes a solar project located in the American Southeast. The selection of this location was made for several reasons:

- The ground cover for a site in the southeast is assumed to be grass with an albedo of 0.25. This is sub optimal from the perspective of backside irradiance gain which makes the results applicable to a wider range of projects.
- Higher number of cloud days which decreases the impact of clipping (see the Bifacial Energy Models Section below for more information on clipping).
- Relatively light climatic structural loading, such that the mechanical rating of the modules when mounted on their short side is not exceeded.

- GameChange has received a growing number of RFPs for projects using bifacial modules in this region.

As the site was held constant for all simulations, the site meteorological and albedo inputs into the SAM program were the same for all configurations. In addition, the following parameters were held constant for all configurations:

- The project DC capacity is assumed to be 28MWdc which yields results applicable both to larger distributed and utility scale projects.
- 385W modules with 70% bifaciality factor are assumed. The bifaciality factor is the ratio of the nominal efficiency of the rear side of the module to the front side of the module. This matches commercially available bifacial modules currently in the market.
- Ten 1500Vdc inverters are assumed. The string size is 28 modules and a clipping ratio (DC/AC ratio) of 1.19 is used.
- The Ground Coverage Ratio (GCR) was held constant at 30% and the Range of Motion (ROM) was held constant at +/- 52 degrees.
- Backtracking is enabled and therefore the theoretical front side shading loss is 0%.

Several parameters were modified in the SAM program to model the behavior of the various mounting configurations. These are summarized in the table below.

Racking Configuration	Module Orientation	Ground Clearance Height	Collector Width	Rear Irradiance Loss Due to Shading
A: 1-Up Portrait	Portrait	1.84m	2m	6.3%
B: 2-Up Landscape	Landscape	1.92m	2m	0%
C: 2-Up Portrait, H=0.7	Portrait	2.72m	4m	0%
D: 2-Up Portrait, H=0.9	Portrait	3.75m	4m	0%

Table 3-1: Bifacial Modeling Parameters

As there is no structure behind the modules in Configurations B, C, and D, the rear side irradiance losses are set to zero. For Configuration A the rear side irradiance loss was set to the percentage of the rear side of the module that is directly shaded by the structure (i.e. the width of the torque tube / the length of the module), which was confirmed by NREL staff to be appropriate. See the NREL paper “Model and Validation of Single-Axis Tracking with Bifacial PV” for more information[2].

3.2 “Control” Energy Model

The 1-Up Portrait monofacial “Control” model yielded an annual energy production of approximately 49.670 MWh. The increase in input from bifaciality is, by virtue of the back side of the module being opaque, 0% and the inverter power clipping is 0.008%. See Appendix 9.1.1 for a copy of the SAM report.

These numbers were compared with the results of the four bifacial module configurations to identify trends and confirm the models were performing the analysis as expected.

As price increase for bifacial modules is relatively small, the control model is not the optimal configuration by inspection as any meaningful increase in energy production from the 1-Up portrait bifacial configuration will yield preferable financial results.

3.3 Bifacial Energy Models

The results of the energy models for the four bifacial configurations are summarized below. See Appendices 9.1.2 through 9.1.5 for copies of the SAM reports for each configuration.

Racking Configuration	Bifacial Gain	Clipping Losses	Annual Energy Production (MWh)
A: 1-Up Portrait	6.866%	-0.095%	53,035
B: 2-Up Landscape	7.487%	-0.117%	53,330
C: 2-Up Portrait, H=0.7	6.322%	-0.073%	52,784
D: 2-Up Portrait, H=0.9	7.374%	-0.112%	53,277

Table 3-2: Bifacial Energy Model Results

As described above, the depth of the shadow behind the modules has a significant impact on the bifacial energy gain. Thus, it is not surprising that Configuration C (2-Up Portrait, H = 0.7), the 2-Up Portrait configuration with the ground clearance of a traditional 1-Up Portrait configuration, exhibited the lowest increased in annual energy production due to bifacial gain.

The 3 remaining configurations all had the same normalized height of roughly 0.9. Again, not surprisingly, Configuration A (1-Up Portrait) exhibited the lowest bifacial gain of the remaining 3 configurations, as a portion of the backside irradiance is obstructed by the torque tube in this configuration. Furthermore, the mismatch of solar irradiance on the backside of the modules in the area of the module in the shadow of the structure vs. the area receiving backside irradiance may have a negative impact on module degradation, but this is outside of the scope of this study.

Of the remaining configurations, B (2-Up Landscape) and D (2-Up Portrait, H=0.9), the bifacial gain is approximately the same. This is to be expected as there is no structure behind the modules in either configuration and the ratio of collector width (chord length) to panel clearance is roughly the same.

In addition, it is worth noting that the gain from bifacial modules is diluted by inverter clipping. Inopportunely, during the middle portion of the day when the backside irradiance is highest, the DC output of the plant is often in excess of the AC capacity and therefore the gain in energy production from the bifacial aspect of the modules is lost. The impact of clipping is reduced in locations with large numbers of cloudy days and as PV plants age due to module degradation as in both of these scenarios the AC capacity of the plant is exceeded less often. Although this study assumes a site located in a relatively cloudy climate, reduced clipping in later years of the project lifetime are not accounted for in the financial analysis below.

4.0 Structural Analysis and Racking Costs

4.1 Background of structural Analysis

Structural analysis was performed on the four single axis tracker configurations described above. The goal of the analysis was to determine the relative size and strength of critical components such as posts, torque tubes, and purlins, which have different loading requirements in each configuration. These relative sizes and strengths were then accounted for in the CAPEX price of the racking system for each configuration in the financial analysis shown below.

The structural analysis performed by GameChange for this study, and for all of its projects, is in accordance with the applicable version of the IBC, which in this case is assumed to reference ASCE7-10. As stated in the Energy Modeling section above, the analysis herein assumes a site in the American Southeast. For the purposes of structural analysis, this yields relatively light climatic loads. The design wind speed is assumed to be 105 mph, the design snow load is assumed to be 5 psf and the seismic load is negligible. The wind speeds are converted to pressures using wind gust coefficients determined through boundary layer wind tunnel testing that was performed by the firm CPP in accordance with Chapter 31 of ASCE7-10[3]. This wind tunnel testing also included checks for dynamic amplification[4] and instability[5].

The structural components used in the tracker tables are high strength (grade 50 or higher) cold formed steel shapes. They are designed in accordance with the applicable sections of the IBC and the AISI S100 standard “North American Specification for the Design of Cold-Formed Steel Structural Members.” The components are galvanized per the ASTM A653 standard. It is assumed that the site does not contain any highly corrosive airborne or subgrade elements.

As is typical in the solar industry, post embedments are determined through full scale pull testing in accordance with IBC Section 1810.3.3. The post embedments shown in this analysis are derived from an empirical rubric created by GameChange based on their experience installing over 3GW of racking. The soil is assumed to be medium to stiff clay.

The structural analysis was reviewed by Scott Van Pelt, a licensed Professional Engineer in multiple states including North Carolina and Florida, in the American Southeast.

4.2 Components Affected by Bifacial Designs

Primarily, three structural components are affected by the differences in the module configurations described above:

- Posts
- Torque Tube (a.k.a. row tube)
- Purlins: the East-West members the modules are directly in contact with

The Post design varies little between Configurations A and B as the posts have essentially the same stickup height (a.k.a. reveal height) and support a similar number of panels. Standard posts for the configurations are on the order of W6x7 for the interior of the array and W6x8.5 for the perimeter. However, the number of panels supported per post increases in the 2-Up Portrait configuration. Furthermore, the stickup height increases for Configuration C and even more so for Configuration D. This results in increased bending moment and slenderness effects on the posts which require they become larger in shape. Configuration C utilizes post sizes of W6x7s for the interior of the array and W6x15s for the perimeter. Pile sizes are even larger for Configuration D at W6x12s for the interior and W6x20s for the perimeter.

The amount of torque applied to the torque tube is directly proportional to table length and proportional to the square of the chord length (a.k.a. collector width). Configurations A and B account for a tracker table 84 modules (3 strings x 28 modules per string) or about 278 feet long and a chord length of approximately 2m. However, the designs for the 2-Up Portrait configurations call for tracker tables 56 modules (each row has 2 strings x 28 modules per string) or 186 feet long and a chord length of approximately 4m. Thus the 2-Up Portrait configurations apply approximately 266% more torque to the torque tube.

The component most impacted by the various configurations is the purlins. For a 1-Up Portrait configuration, the purlins can be relatively short, often just 18” in length to support modules with mounting holes with 400mm spacing. This short distance reduces the bending moment in the purlins allowing them to be a light gauge. By contrast, the 2-Up Landscape configuration, calls for purlins to be approximately 79” in length. This allows the purlins to extend almost the entire length of the short side of the modules to support them. This longer length results in a larger bending moment and therefore requires the use of a thicker gauge. Finally, a 2-Up Portrait configuration requires the longest purlins, more than 100” in length, to reach more than half way along the long side of the modules. This creates the largest bending moment in the purlins and therefore requires the thickest gauge or additional components below the row tube to create a truss.

It is worth noting that both the 1-Up and 2-Up Portrait configurations call for the modules to be mounted on the long side. The 2-Up Landscape configuration calls for mounting on the short side. There are structural advantages to long side mounting and therefore, some module manufacturers may reduce their mechanical load ratings for short side mounting. This study assumes a location with relatively light climatic loading such that the modules still have sufficient capacity to be mounted on the short side.

4.3 Relative Racking System Cost

Based on the relative sizing of the posts, row tubes, and purlins referenced above, cost per watt of the different configurations relative to a traditional 1-Up Portrait monofacial configuration are shown below:

Racking Configuration	Relative Cost per Watt
A: 1-Up Portrait	+ $0.0000
B: 2-Up Landscape	+ $0.0070
C: 2-Up Portrait, H=0.7	+ $0.0150
D: 2-Up Portrait, H=0.9	> + $0.0250

Table 4-1: Racking costs relative to traditional 1-Up Portrait Monofacial

5.0 Installation Costs

5.1 Allowances for Relative Installation Costs

While installation costs will vary based on the installer / EPC and the size of the project, it is important to this analysis that some allowance be included to account for general trends in the installation costs of the mounting configurations considered. Based on conversations with EPCs who are actively pursuing projects with bifacial modules the following allowances are made for relative cost per watt to install the different configurations. These prices are relative to a traditional 1-Up Portrait monofacial configuration:

Racking Configuration	Relative Cost per Watt
A: 1-Up Portrait	+ $0.0000
B: 2-Up Landscape	+ $0.0110
C: 2-Up Portrait, H=0.7	+ $0.0060
D: 2-Up Portrait, H=0.9	> + $0.0210

Table 5-1: Installation costs relative to traditional 1-Up Portrait Monofacial

The prices above account for the following:

- It is expected that in all but the 1-Up Portrait configuration, a first row of modules will be installed and then time will be spent rotating the tracker tables to install the 2nd row of modules
- The pile count per MW is meaningfully lower for the 2-Up Portrait configurations and therefore pile driving costs are proportionally lower.

- Purlin count for the 1-Up Portrait configuration is double the count for the 2-Up configurations.
- The elevation of the row tube above grade for Configuration D (2-Up Portrait, H=0.9) is sufficiently high enough that OSHA fall protection measures will be required for multiple steps of the installation. These requirements will slow down production rates and add meaningful cost to the installation.
- All configurations are assumed to utilize a traditional bottom mount connection between the module and the racking structure. This calls for the module frame to be fastened to the racking structure with 4 bolts per module.

As stated above, while Configuration D (2-Up Portrait, H = 0.9) has advantages from a backside irradiance gain standpoint, the increased post stickup height causes the cost of the racking structure, in particular the posts of the tracker table, to increase more than 2 cents per watt. Furthermore, the increased height of the torque tube greatly increases the complexity and therefore cost of installation in regards to fall protection. As such, although energy modeling was performed for this configuration, financial analysis was not performed as it is not the optimal configuration by inspection.

6.0 Financial Analysis

6.1 Financial Model

A financial model was created for each of the following configurations:

- Configuration A: 1-Up Portrait, H = 0.9
- Configuration B: 2-Up Landscape, H = 0.9
- Configuration C: 2-Up Portrait, H = 0.7

For the reasons stated above it is not meaningful to perform financial analysis for either the 1-Up Portrait monofacial “control” configuration or Configuration D (2-Up Portrait, H = .90).

The financial models account for the following:

- System CAPEX: As stated above, this study assumes a 28MWdc solar project. An installed cost of $1.11 per Watt is assumed for the traditional, 1-Up Portrait, configuration based on the NREL report “U.S. Solar Photovoltaic System Cost Benchmark”[6]. The cost per watt for the 2-Up Landscape and 2-Up Portrait configurations were increased to account for the relative costs described in Sections 4 and 5 above.
- Solar Power Degradation: Degradation of 2% is assumed during the first year and 0.5% for all subsequent years for all configurations. See the note below regarding possible accelerated degradation of bifacial modules in a 1-Up Portrait configuration.
- Energy Revenue: Revenues of $0.0304 / kWh are assigned to the annual energy production estimates described in Section 3 above, accounting for the module degradation. A 3% yearly increase in the price of electricity is also assumed.
- O&M: Operations and maintenance costs of $37,800 are assumed. This is appropriate for a non-ganged single axis tracker. See the white paper: “Financial and Risk Analysis on Three Solar Tracker Designs”[7] by GameChange for more information.
- Design Life: A 30-year design life of the solar power plant is assumed.

A few additional notes on the financial assumptions:

- As of the writing of this report, it is understood that structure obstructing a portion of the backside of bifacial modules, such as the impact of the torque tube in a 1-Up Portrait configuration, creates hot spots due to the mismatch of irradiation on the rear side of the cells between the portion of the cell in the shadow of the structure and the portion of the cell receiving the rear side irradiance. It is not fully understood how large an impact this mismatch has on the longevity of the solar panel and therefore no increase in module degradation is accounted for. However, readers of this report should be aware that there is a possibility of accelerated degradation of the modules due to this mismatch which would have negative impacts on project financials accordingly.

- This analysis does not account for the debt structure of the project ownership. Increased ROE resulting from additional energy produced by bifacial modules being levered by project debt is outside the scope of this study as is interest costs associated with the various configurations.

6.2 Financial Results

Based on the above parameters, the costs and revenue for each month are calculated. Subsequently, the project CAPEX, total energy produced, levelized cost of energy (LCOE), and internal rate of return (IRR) are computed. These are summarized in the table below. See Appendices 9.2.1 through 9.2.3 for details of the financial analysis.

Racking Configuration	Project CAPEX ($MM)	Total Energy Produced (GWh)	LCOE ($/kWh)	IRR (%)
A: 1-Up Portrait	$31.080	1,449	$0.0222	5.19%
B: 2-Up Landscape	$31.584	1.457	$0.0225	5.11%
C: 2-Up Portrait, H=0.7	$31.668	1.442	$0.0228	5.01%

Table 6-1: Financial Model Results

The LCOE and IRR for the 1-Up Portrait configuration showed the most preferable results followed by the 2-Up Landscape configuration. The financial parameters for the project are worst for Configuration C.

7.0 Conclusions

Four potential mounting configurations for bifacial modules were analyzed, accounting for relative costs in racking structure, installation and relative energy production. The financial analysis of these configurations showed that the 1-Up Portrait configuration provides the best financial performance for project ownership. This is followed by the 2-Up Landscape configuration for a project, provided the climatic loads do not exceed the short-side mounting mechanical ratings of the module. The 2-Up Portrait configuration provides the worst financial performance for the project ownership.

This analysis does not account for a potential increase in the degradation rate of bifacial modules due to racking structure partially shading the backside of the modules, thus creating an irradiance mismatch. It is the understanding of the authors of this paper that in the near future studies will be performed to quantify the impact of partial shading of the backside of bifacial modules on typical degradation rates. In the meantime, it is recommended that project owners utilize 2-Up Landscape configurations when mounting bifacial solar modules on single axis trackers in locations with relatively light climatic loads.

8.0 Bibliography

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6. Fu, Ran, David Feldman, Robert Margolis, Mike Woodhouse, and Kristen Ardani. U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017. Golden, National Renewable Energy Lab: 2017.
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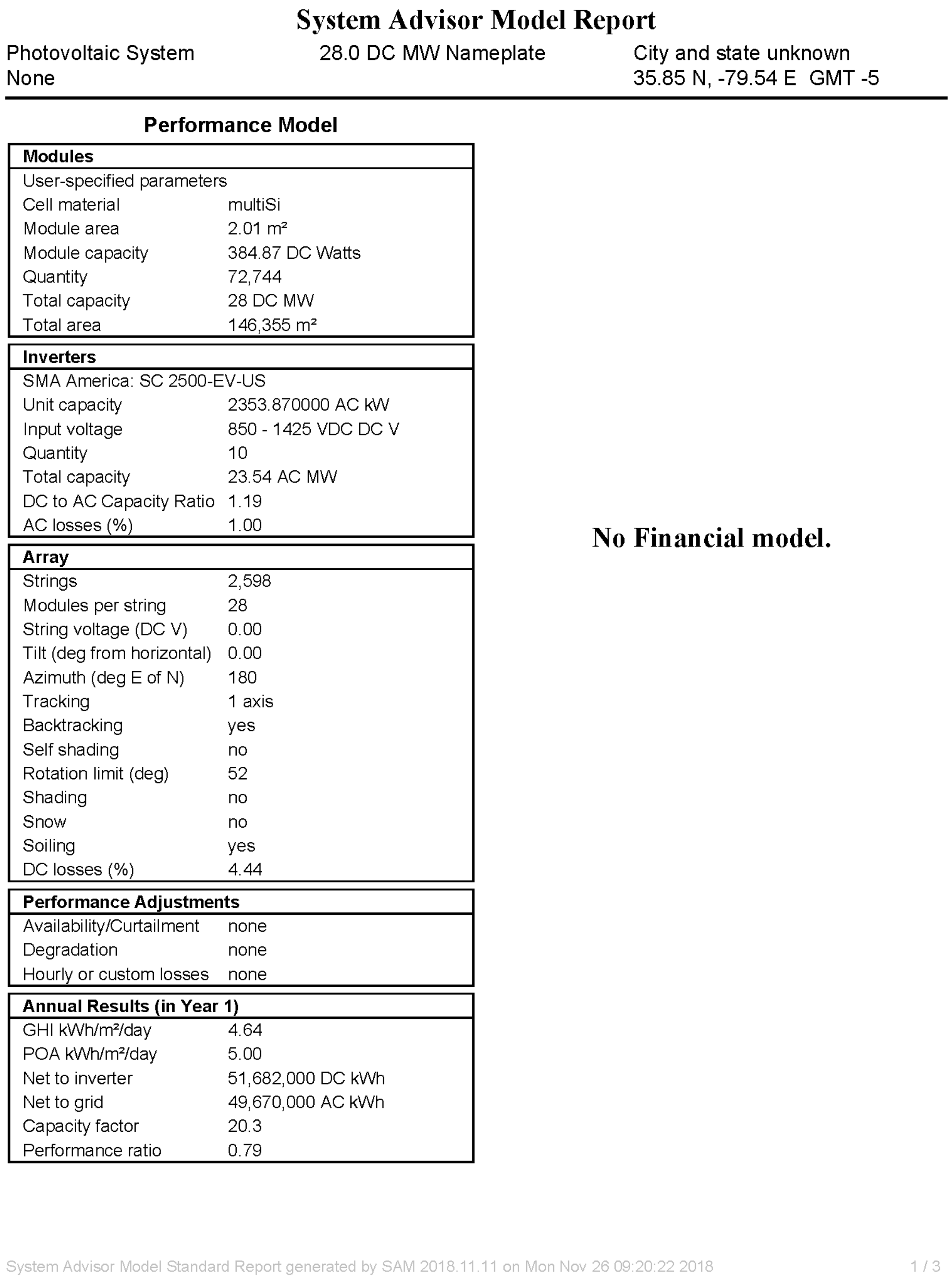
9.0 Appendicies

9.1 Energy Models

9.1.1 1-Up Portrait Monofacial "Control" Energy Model



System Advisor Model Report

Photovoltaic System	28.0 DC MW Nameplate	City and state unknown
None		35.85 N, -79.54 E GMT -5

Performance Model

Modules	
User-specified parameters	
Cell material	multiSi
Module area	2.01 m²
Module capacity	384.87 DC Watts
Quantity	72,744
Total capacity	28 DC MW
Total area	146,355 m²

Inverters	
SMA America: SC 2500-EV-US	
Unit capacity	2353.870000 AC kW
Input voltage	850 - 1425 VDC DC V
Quantity	10
Total capacity	23.54 AC MW
DC to AC Capacity Ratio	1.19
AC losses (%)	1.00

Array	
Strings	2,598
Modules per string	28
String voltage (DC V)	0.00
Tilt (deg from horizontal)	0.00
Azimuth (deg E of N)	180
Tracking	1 axis
Backtracking	yes
Self shading	no
Rotation limit (deg)	52
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.44

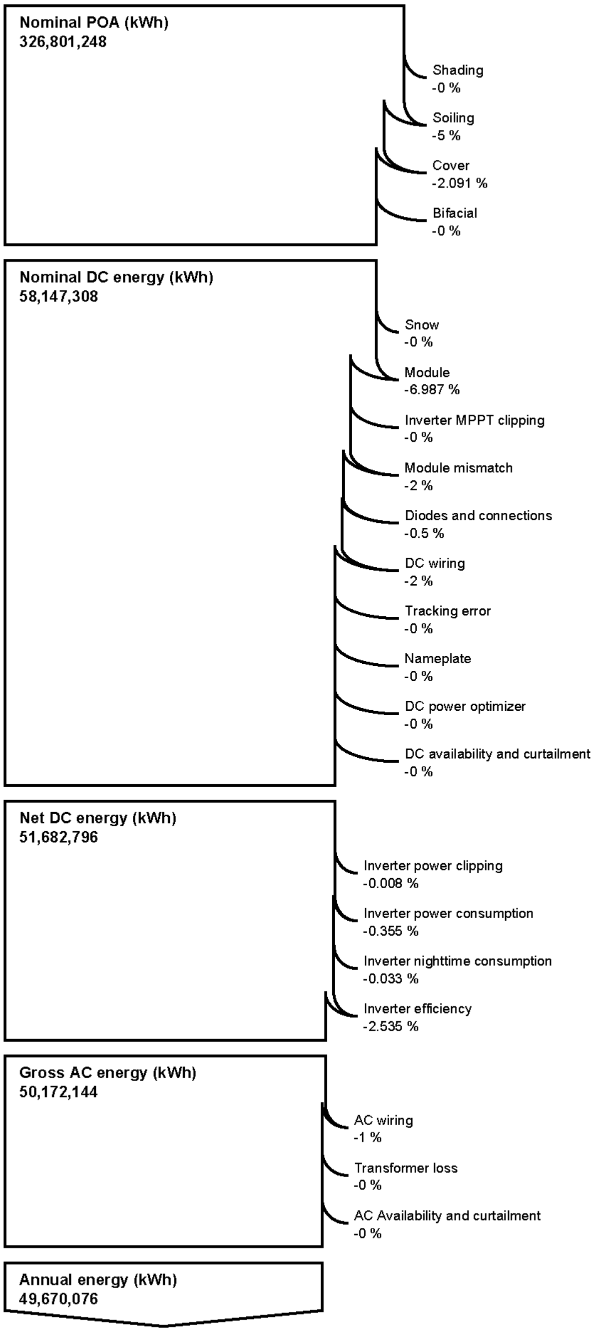
Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	4.64
POA kWh/m²/day	5.00
Net to inverter	51,682,000 DC kWh
Net to grid	49,670,000 AC kWh
Capacity factor	20.3
Performance ratio	0.79

No Financial model.

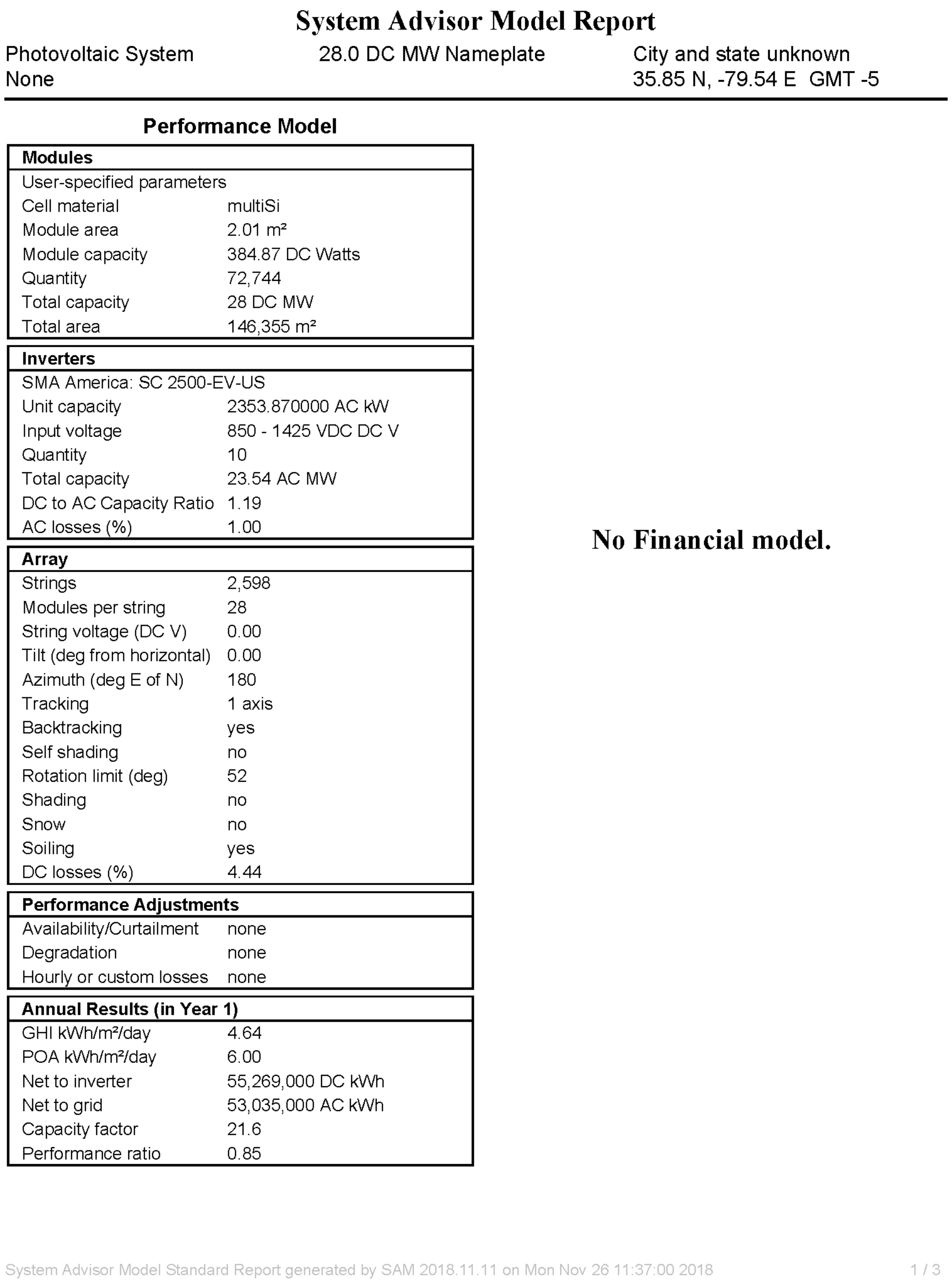
System Advisor Model Standard Report generated by SAM 2018.11.11 on Mon Nov 26 09:20:22 2018 1 / 3

Photovoltaic System	28.0 DC MW Nameplate	City and state unknown
None		35.85 N, -79.54 E GMT -5



None | Flat Plate PV | Simple Efficiency Module Model | Sandia Inverter Database

9.1.2 1-Up Portrait Bifacial Energy Model



System Advisor Model Report

Photovoltaic System None	28.0 DC MW Nameplate	City and state unknown 35.85 N, -79.54 E GMT -5

Performance Model

Modules	
User-specified parameters	
Cell material	multiSi
Module area	2.01 m²
Module capacity	384.87 DC Watts
Quantity	72,744
Total capacity	28 DC MW
Total area	146,355 m²

Inverters	
SMA America: SC 2500-EV-US	
Unit capacity	2353.870000 AC kW
Input voltage	850 - 1425 VDC DC V
Quantity	10
Total capacity	23.54 AC MW
DC to AC Capacity Ratio	1.19
AC losses (%)	1.00

Array	
Strings	2,598
Modules per string	28
String voltage (DC V)	0.00
Tilt (deg from horizontal)	0.00
Azimuth (deg E of N)	180
Tracking	1 axis
Backtracking	yes
Self shading	no
Rotation limit (deg)	52
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.44

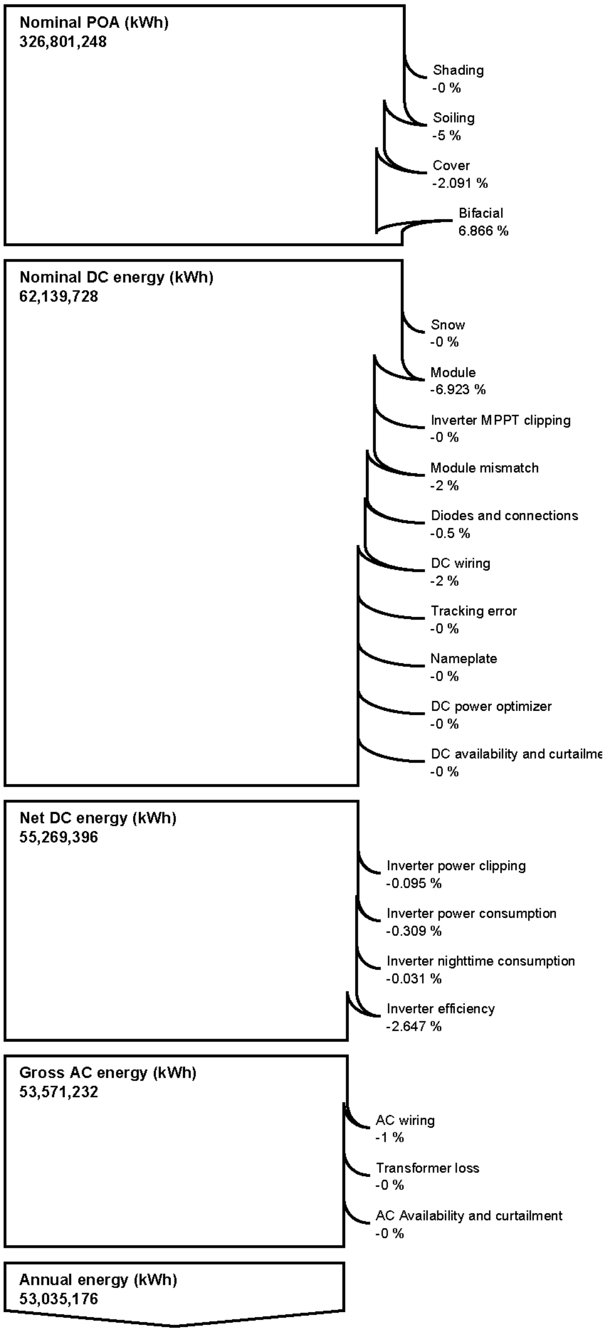
Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	4.64
POA kWh/m²/day	6.00
Net to inverter	55,269,000 DC kWh
Net to grid	53,035,000 AC kWh
Capacity factor	21.6
Performance ratio	0.85

No Financial model.

System Advisor Model Standard Report generated by SAM 2018.11.11 on Mon Nov 26 11:37:00 2018 1 / 3

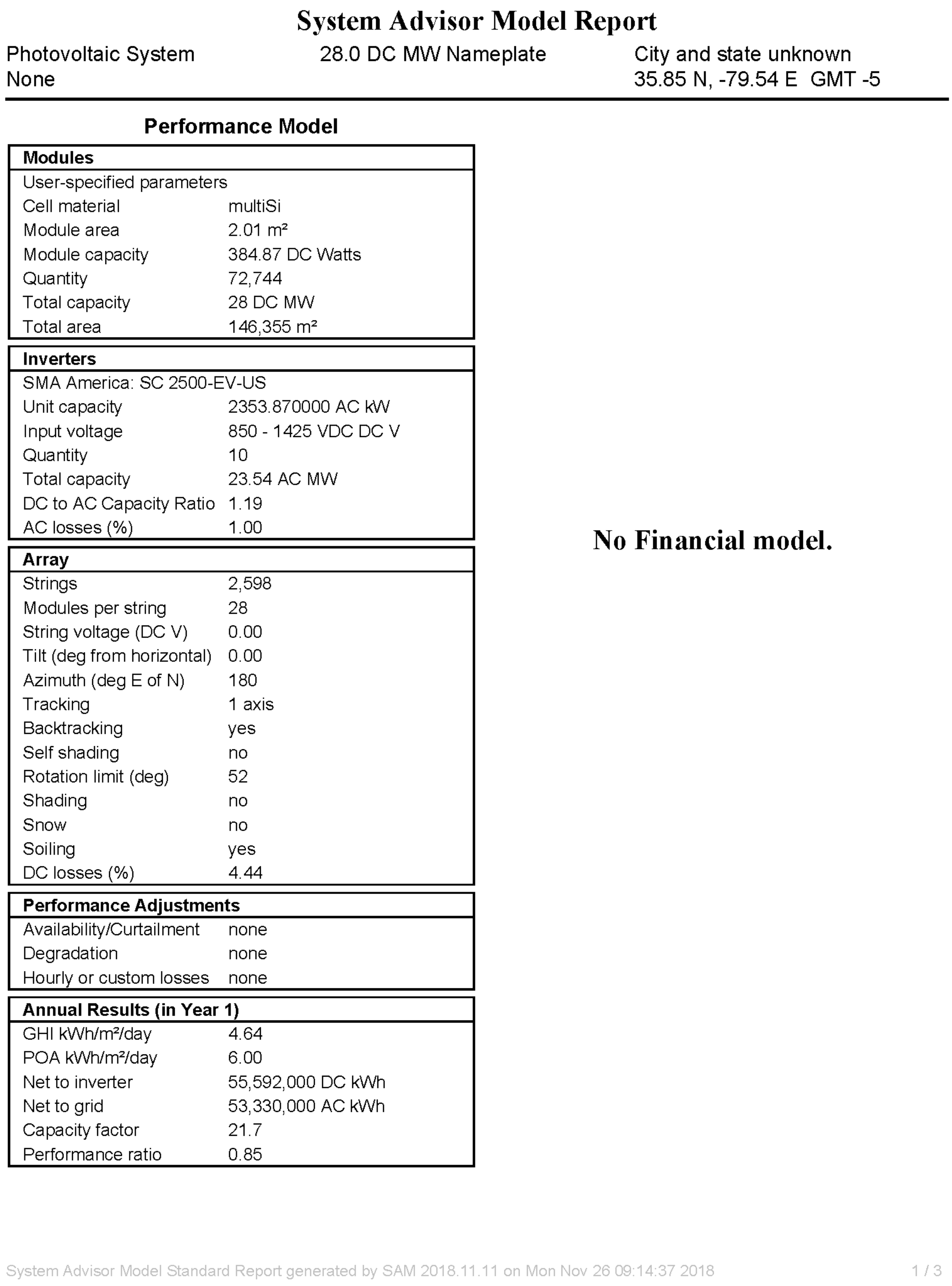
Photovoltaic System 28.0 DC MW Nameplate City and state unknown
None 35.85 N, -79.54 E GMT -5



None | Flat Plate PV | Simple Efficiency Module Model | Sandia Inverter Database

System Advisor Model Standard Report generated by SAM 2018.11.11 on Mon Nov 26 11:37:00 2018 3 / 3

9.1.3 2-Up Landscape Bifacial Energy Model



System Advisor Model Report

Photovoltaic System	28.0 DC MW Nameplate	City and state unknown
None		35.85 N, -79.54 E GMT -5

Performance Model

Modules	
User-specified parameters	
Cell material	multiSi
Module area	2.01 m²
Module capacity	384.87 DC Watts
Quantity	72,744
Total capacity	28 DC MW
Total area	146,355 m²

Inverters	
SMA America: SC 2500-EV-US	
Unit capacity	2353.870000 AC kW
Input voltage	850 - 1425 VDC DC V
Quantity	10
Total capacity	23.54 AC MW
DC to AC Capacity Ratio	1.19
AC losses (%)	1.00

Array	
Strings	2,598
Modules per string	28
String voltage (DC V)	0.00
Tilt (deg from horizontal)	0.00
Azimuth (deg E of N)	180
Tracking	1 axis
Backtracking	yes
Self shading	no
Rotation limit (deg)	52
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.44

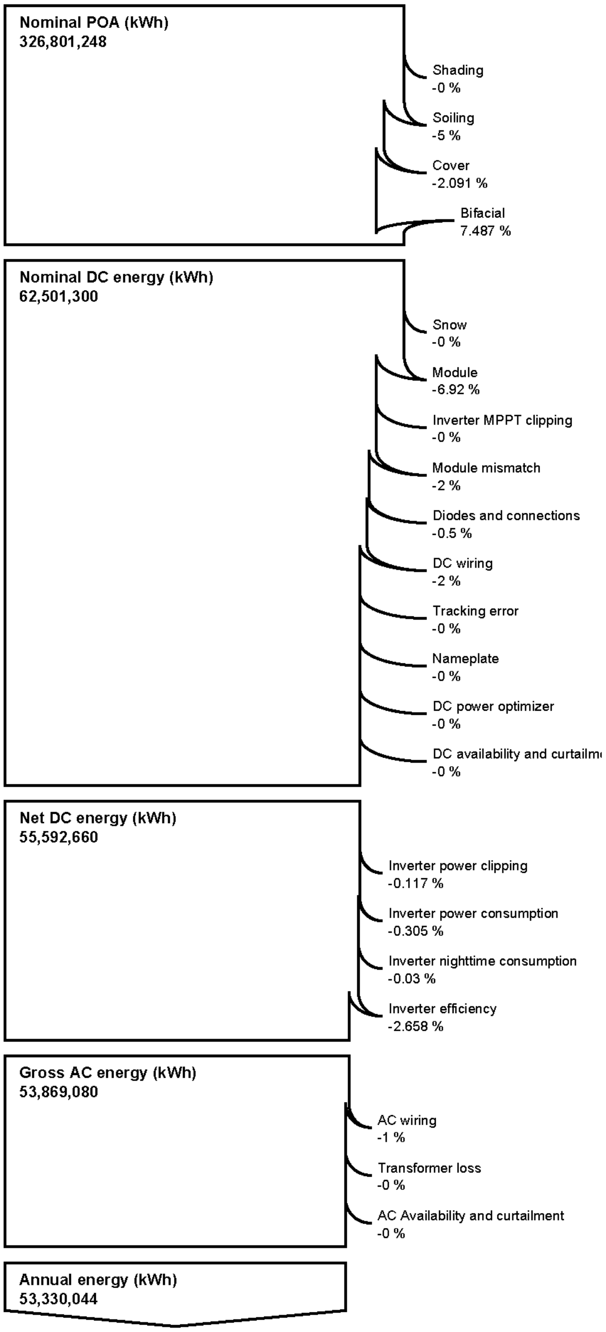
Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	4.64
POA kWh/m²/day	6.00
Net to inverter	55,592,000 DC kWh
Net to grid	53,330,000 AC kWh
Capacity factor	21.7
Performance ratio	0.85

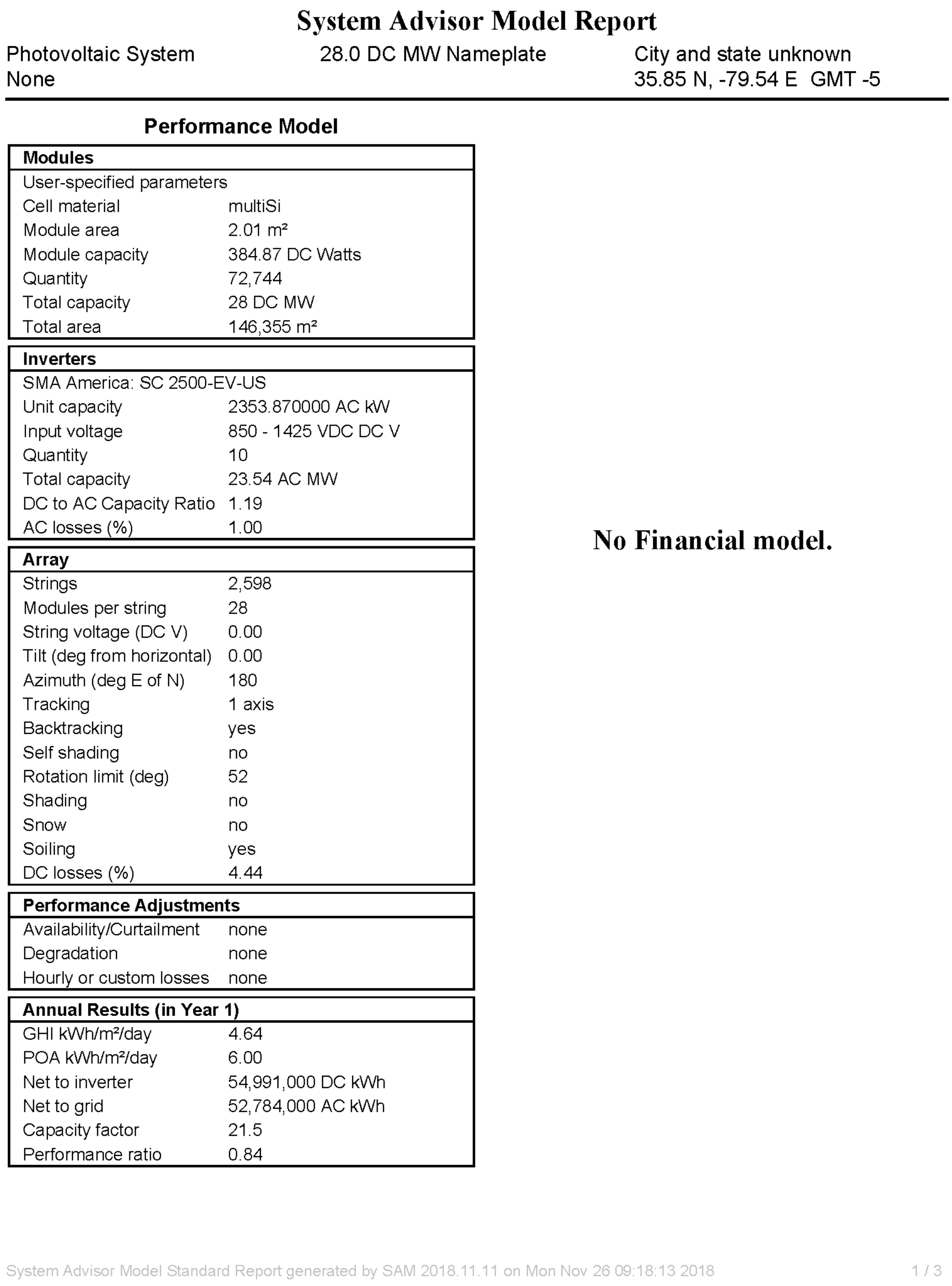
No Financial model.

System Advisor Model Standard Report generated by SAM 2018.11.11 on Mon Nov 26 09:14:37 2018 1 / 3

Photovoltaic System	28.0 DC MW Nameplate	City and state unknown
None		35.85 N, -79.54 E GMT -5



9.1.4 2-Up Portait, H=0.7 Bifacial Energy Model



System Advisor Model Report

Photovoltaic System	28.0 DC MW Nameplate	City and state unknown
None		35.85 N, -79.54 E GMT -5

Performance Model

Modules	
User-specified parameters	
Cell material	multiSi
Module area	2.01 m²
Module capacity	384.87 DC Watts
Quantity	72,744
Total capacity	28 DC MW
Total area	146,355 m²

Inverters	
SMA America: SC 2500-EV-US	
Unit capacity	2353.870000 AC kW
Input voltage	850 - 1425 VDC DC V
Quantity	10
Total capacity	23.54 AC MW
DC to AC Capacity Ratio	1.19
AC losses (%)	1.00

Array	
Strings	2,598
Modules per string	28
String voltage (DC V)	0.00
Tilt (deg from horizontal)	0.00
Azimuth (deg E of N)	180
Tracking	1 axis
Backtracking	yes
Self shading	no
Rotation limit (deg)	52
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.44

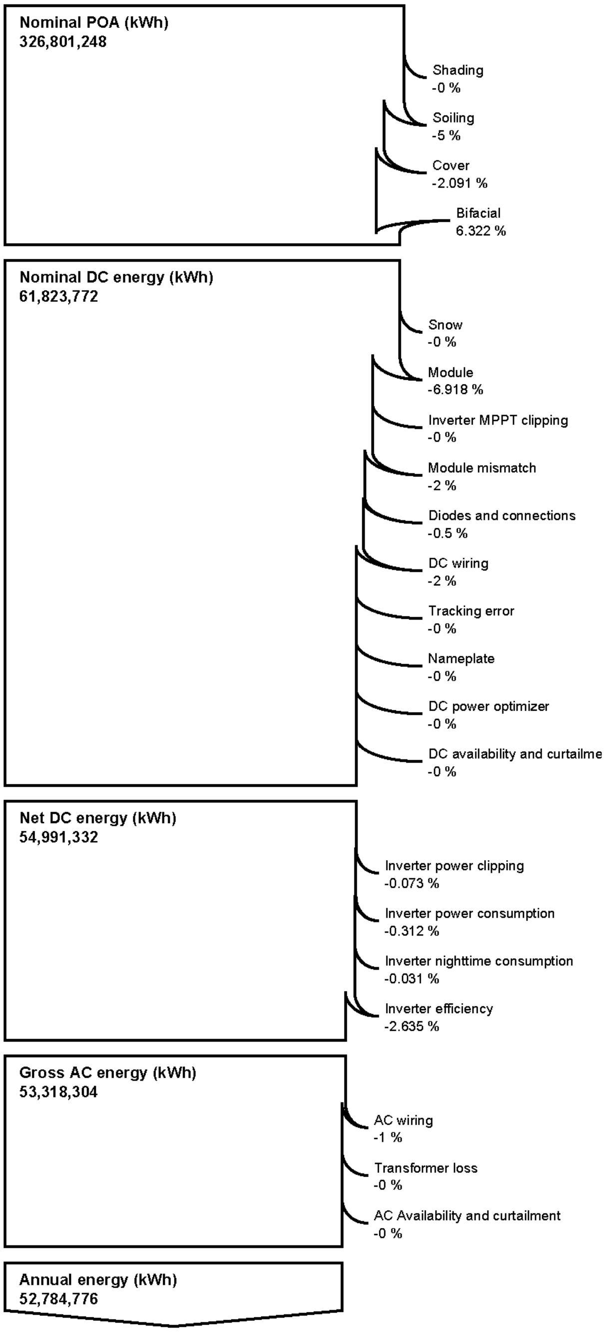
Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	4.64
POA kWh/m²/day	6.00
Net to inverter	54,991,000 DC kWh
Net to grid	52,784,000 AC kWh
Capacity factor	21.5
Performance ratio	0.84

No Financial model.

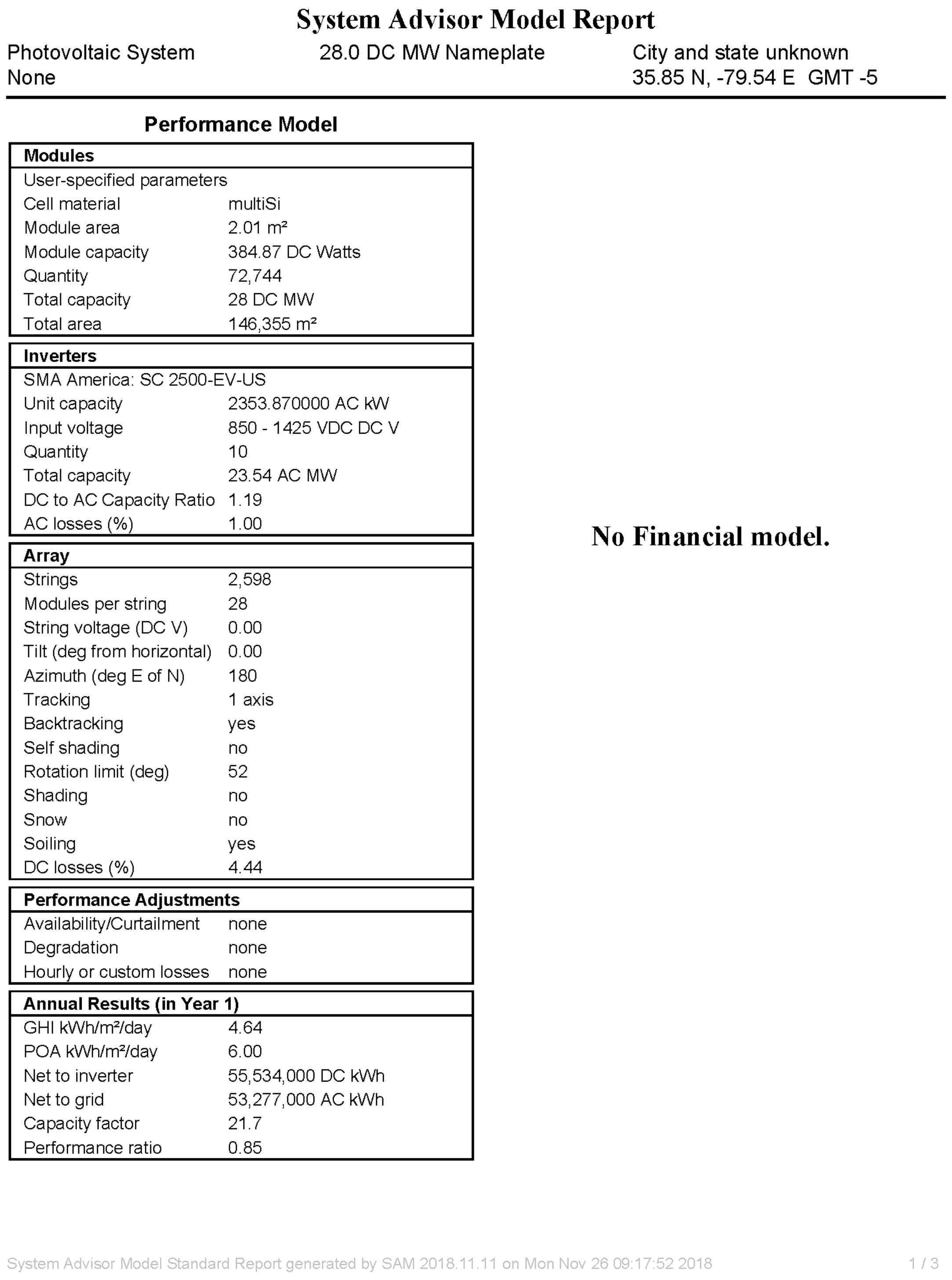
System Advisor Model Standard Report generated by SAM 2018.11.11 on Mon Nov 26 09:18:13 2018 1 / 3

Photovoltaic System	28.0 DC MW Nameplate	City and state unknown
None		35.85 N, -79.54 E GMT -5



None | Flat Plate PV | Simple Efficiency Module Model | Sandia Inverter Database

9.1.5 2-Up Portait, H=0.9 Bifacial Energy Model



System Advisor Model Report

Photovoltaic System	28.0 DC MW Nameplate	City and state unknown
None		35.85 N, -79.54 E GMT -5

Performance Model

Modules	
User-specified parameters	
Cell material	multiSi
Module area	2.01 m²
Module capacity	384.87 DC Watts
Quantity	72,744
Total capacity	28 DC MW
Total area	146,355 m²

Inverters	
SMA America: SC 2500-EV-US	
Unit capacity	2353.870000 AC kW
Input voltage	850 - 1425 VDC DC V
Quantity	10
Total capacity	23.54 AC MW
DC to AC Capacity Ratio	1.19
AC losses (%)	1.00

Array	
Strings	2,598
Modules per string	28
String voltage (DC V)	0.00
Tilt (deg from horizontal)	0.00
Azimuth (deg E of N)	180
Tracking	1 axis
Backtracking	yes
Self shading	no
Rotation limit (deg)	52
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.44

Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	none

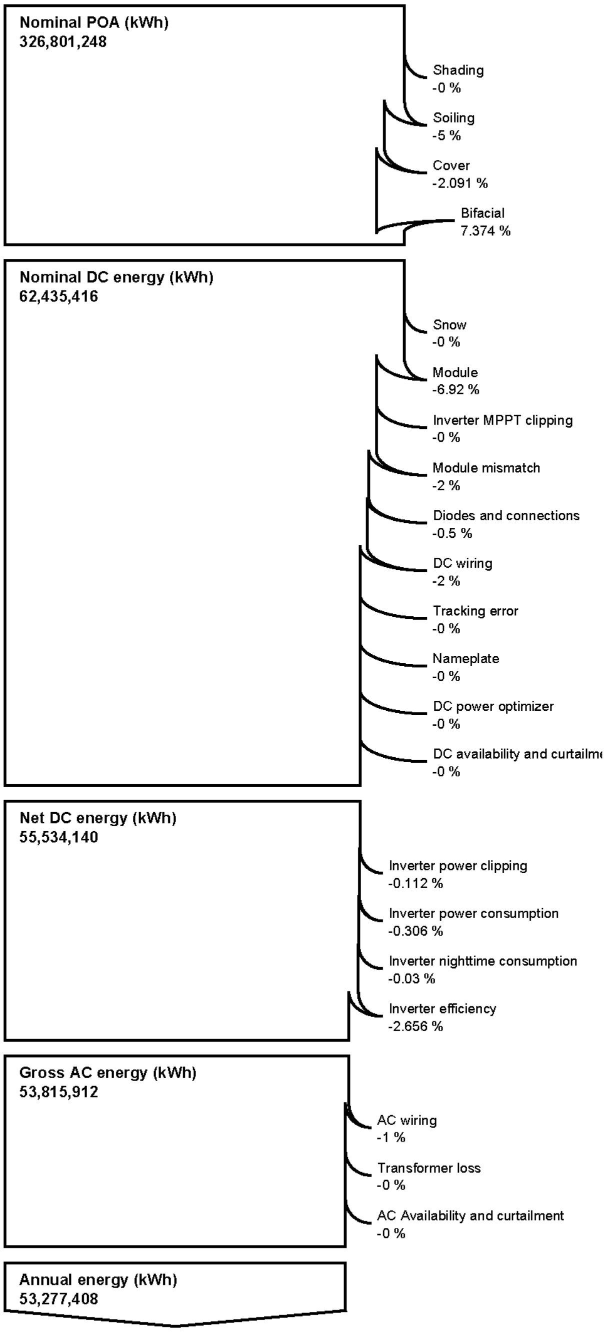
Annual Results (in Year 1)	
GHI kWh/m²/day	4.64
POA kWh/m²/day	6.00
Net to inverter	55,534,000 DC kWh
Net to grid	53,277,000 AC kWh
Capacity factor	21.7
Performance ratio	0.85

No Financial model.

System Advisor Model Standard Report generated by SAM 2018.11.11 on Mon Nov 26 09:17:52 2018 1 / 3

Photovoltaic System | 28.0 DC MW Nameplate | City and state unknown

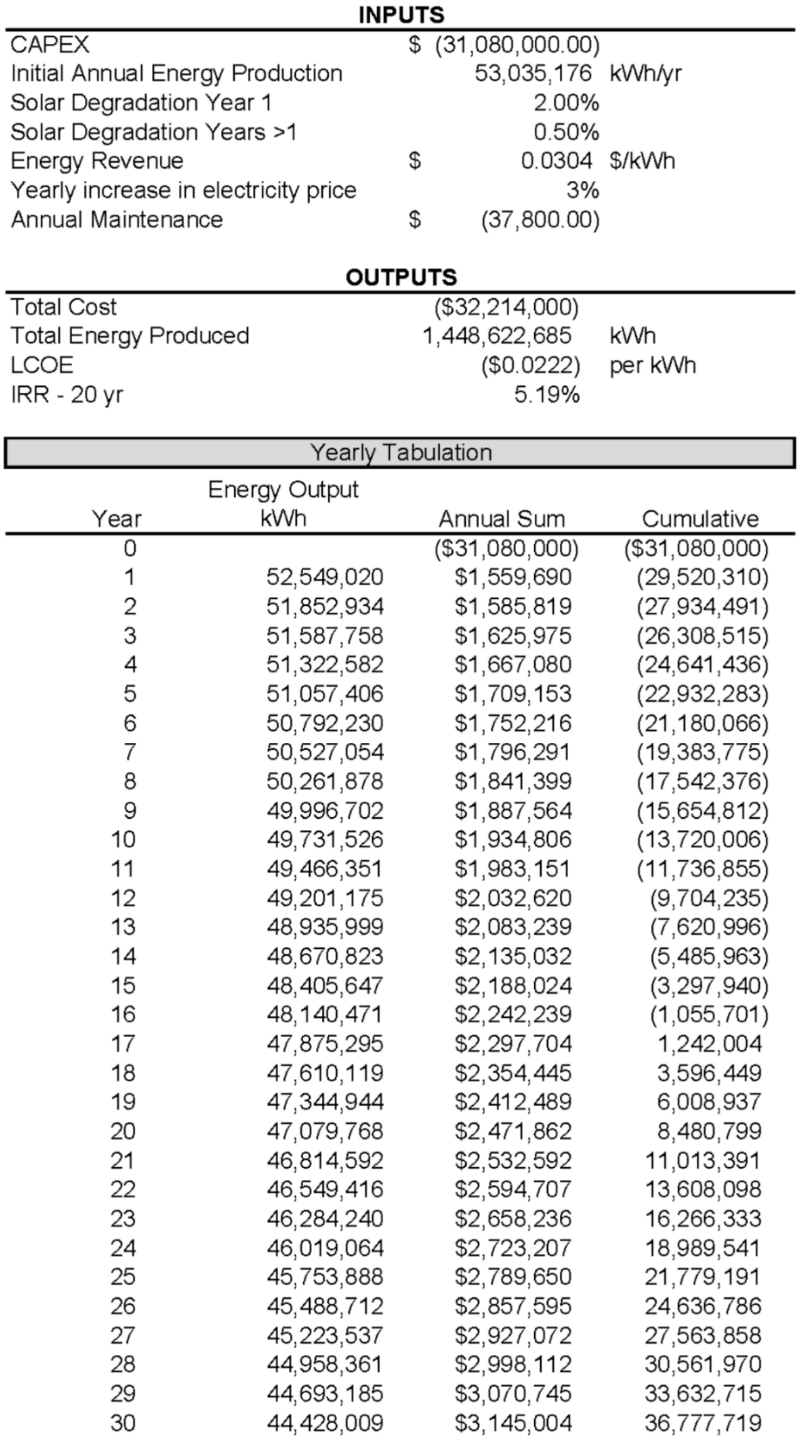
None | | 35.85 N, -79.54 E GMT -5



None | Flat Plate PV | Simple Efficiency Module Model | Sandia Inverter Database

9.2 Financial Models

9.2.1 1- Up Portrait Bifacial Financial Model



INPUTS

CAPEX	$	(31,080,000.00)	
Initial Annual Energy Production		53,035,176	kWh/yr
Solar Degradation Year 1		2.00%	
Solar Degradation Years >1		0.50%	
Energy Revenue	$	0.0304	$/kWh
Yearly increase in electricity price		3%	
Annual Maintenance	$	(37,800.00)	

OUTPUTS

Total Cost	($32,214,000)	
Total Energy Produced	1,448,622,685	kWh
LCOE	($0.0222)	per kWh
IRR - 20 yr	5.19%	

Yearly Tabulation

Year	Energy Output kWh	Annual Sum	Cumulative
0		($31,080,000)	($31,080,000)
1	52,549,020	$1,559,690	(29,520,310)
2	51,852,934	$1,585,819	(27,934,491)
3	51,587,758	$1,625,975	(26,308,515)
4	51,322,582	$1,667,080	(24,641,436)
5	51,057,406	$1,709,153	(22,932,283)
6	50,792,230	$1,752,216	(21,180,066)
7	50,527,054	$1,796,291	(19,383,775)
8	50,261,878	$1,841,399	(17,542,376)
9	49,996,702	$1,887,564	(15,654,812)
10	49,731,526	$1,934,806	(13,720,006)
11	49,466,351	$1,983,151	(11,736,855)
12	49,201,175	$2,032,620	(9,704,235)
13	48,935,999	$2,083,239	(7,620,996)
14	48,670,823	$2,135,032	(5,485,963)
15	48,405,647	$2,188,024	(3,297,940)
16	48,140,471	$2,242,239	(1,055,701)
17	47,875,295	$2,297,704	1,242,004
18	47,610,119	$2,354,445	3,596,449
19	47,344,944	$2,412,489	6,008,937
20	47,079,768	$2,471,862	8,480,799
21	46,814,592	$2,532,592	11,013,391
22	46,549,416	$2,594,707	13,608,098
23	46,284,240	$2,658,236	16,266,333
24	46,019,064	$2,723,207	18,989,541
25	45,753,888	$2,789,650	21,779,191
26	45,488,712	$2,857,595	24,636,786
27	45,223,537	$2,927,072	27,563,858
28	44,958,361	$2,998,112	30,561,970
29	44,693,185	$3,070,745	33,632,715
30	44,428,009	$3,145,004	36,777,719

9.2.2 2-Up Landscape Bifacial Financial Model

INPUTS

CAPEX	$	(31,584,000.00)	
Initial Annual Energy Production		53,330,044	kWh/yr
Solar Degradation Year 1		2.00%	
Solar Degradation Years >1		0.50%	
Energy Revenue	$	0.0304	$/kWh
Yearly increase in electricity price		3%	
Annual Maintenance	$	(37,800.00)	

OUTPUTS

Total Cost	($32,718,000)	
Total Energy Produced	1,456,676,821	kWh
LCOE	($0.0225)	per kWh
IRR - 20 yr	5.11%	

Yearly Tabulation

Year	Energy Output kWh	Annual Sum	Cumulative
0		($31,584,000)	($31,584,000)
1	52,841,185	$1,568,572	(30,015,428)
2	52,141,228	$1,594,846	(28,420,582)
3	51,874,578	$1,635,226	(26,785,356)
4	51,607,928	$1,676,559	(25,108,797)
5	51,341,278	$1,718,866	(23,389,932)
6	51,074,628	$1,762,169	(21,627,763)
7	50,807,977	$1,806,488	(19,821,275)
8	50,541,327	$1,851,848	(17,969,427)
9	50,274,677	$1,898,268	(16,071,159)
10	50,008,027	$1,945,774	(14,125,385)
11	49,741,376	$1,994,387	(12,130,998)
12	49,474,726	$2,044,132	(10,086,867)
13	49,208,076	$2,095,032	(7,991,835)
14	48,941,426	$2,147,113	(5,844,722)
15	48,674,776	$2,200,399	(3,644,323)
16	48,408,125	$2,254,916	(1,389,407)
17	48,141,475	$2,310,689	921,282
18	47,874,825	$2,367,746	3,289,028
19	47,608,175	$2,426,112	5,715,139
20	47,341,524	$2,485,815	8,200,954
21	47,074,874	$2,546,883	10,747,837
22	46,808,224	$2,609,343	13,357,181
23	46,541,574	$2,673,225	16,030,406
24	46,274,924	$2,738,558	18,768,964
25	46,008,273	$2,805,371	21,574,335
26	45,741,623	$2,873,693	24,448,028
27	45,474,973	$2,943,556	27,391,584
28	45,208,323	$3,014,991	30,406,575
29	44,941,672	$3,088,028	33,494,603
30	44,675,022	$3,162,700	36,657,303

9.2.3 2-Up Portrait Bifacial, H=0.7 Financial Model

INPUTS

CAPEX	$	(31,668,000.00)	
Initial Annual Energy Production		52,784,776	kWh/yr
Solar Degradation Year 1		2.00%	
Solar Degradation Years >1		0.50%	
Energy Revenue	$	0.0304	$/kWh
Yearly increase in electricity price		3%	
Annual Maintenance	$	(37,800.00)	

OUTPUTS

Total Cost	($32,802,000)	
Total Energy Produced	1,441,783,166	kWh
LCOE	($0.0228)	per kWh
IRR - 20 yr	5.01%	

Yearly Tabulation

Year	Energy Output kWh	Annual Sum	Cumulative
0		($31,668,000)	($31,668,000)
1	52,300,916	$1,552,148	(30,115,852)
2	51,608,115	$1,578,153	(28,537,699)
3	51,344,191	$1,618,120	(26,919,579)
4	51,080,268	$1,659,030	(25,260,549)
5	50,816,344	$1,700,905	(23,559,644)
6	50,552,420	$1,743,765	(21,815,879)
7	50,288,496	$1,787,632	(20,028,247)
8	50,024,572	$1,832,527	(18,195,720)
9	49,760,648	$1,878,473	(16,317,247)
10	49,496,724	$1,925,493	(14,391,754)
11	49,232,800	$1,973,609	(12,418,145)
12	48,968,877	$2,022,845	(10,395,300)
13	48,704,953	$2,073,225	(8,322,075)
14	48,441,029	$2,124,773	(6,197,302)
15	48,177,105	$2,177,515	(4,019,787)
16	47,913,181	$2,231,474	(1,788,313)
17	47,649,257	$2,286,677	498,365
18	47,385,333	$2,343,150	2,841,515
19	47,121,409	$2,400,920	5,242,435
20	46,857,486	$2,460,012	7,702,447
21	46,593,562	$2,520,456	10,222,903
22	46,329,638	$2,582,278	12,805,181
23	46,065,714	$2,645,507	15,450,688
24	45,801,790	$2,710,171	18,160,859
25	45,537,866	$2,776,301	20,937,160
26	45,273,942	$2,843,925	23,781,085
27	45,010,018	$2,913,074	26,694,159
28	44,746,094	$2,983,778	29,677,936
29	44,482,171	$3,056,068	32,734,005
30	44,218,247	$3,129,977	35,863,982